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Arnold Schwarzenegger
Governor

INNOVATIVE WHEEL CONCEPT TO INCREASE GAS TURBINE EFFICIENCY

INDEPENDENT ASSESSMENT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program
Energy Innovations Small Grants Program

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration
- Transportation
- Energy Innovations Small Grant Program

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million, five percent of which is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)

- Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the California Energy Commission's website at http://www.energy.ca.gov/research/index.html.

Abstract

The purpose of this project was to validate an innovative small gas turbine wheel concept which could be incorporated into a conventional recuperated Brayton-cycle gas turbine framework to achieve an efficiency of approximately 40 percent at a turbine inlet temperature of 1,700° F. This new wheel concept is based on the elimination or reduction of "wheel exit" losses and the efficient operation at a low pressure ratio which together would produce a 30 percent increase in overall system efficiency when compared to other small radial or multi-staged axial flow machines (less than five megawatts) at similar operating temperatures. This efficiency gain is based on the use of the new wheel in a conventional recuperated Brayton cycle with all typical losses (nozzle losses, windage, pressure drops in recuperator and combustor, heat losses, etc.) accounted for in the cycle analysis.

The advantages of this new wheel concept were twofold. First, this new wheel idea would convert the exhaust loss (kinetic energy) indigenous to radial and axial flow machines which can be as high as 25 percent, and other losses associated with a rotating bladed wheel (e.g.: clearance losses and cosine losses) into usable shaft energy. Second, the overall cycle using this new wheel could operate at very low rates of compression (two to one for single stage, and four to one for two stages) which allows for high rates of recuperation.

Preliminary and final drawings for the wheel and an experimental test stand were prepared as part of the scope of work. Then a critical study was done to analyze more closely the losses and theoretical performance of the wheel prior to physical experimentation. The results of the study indicated that the net wheel output and performance would be substantially less than originally projected and these results led to a termination of the project. Finally, it was recommended that no future work be pursued regarding this type of wheel concept.

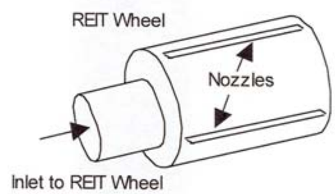
Keywords: turbine, wheel, micro-turbine, impulse, efficiency, Hero, radial, axial, sonic.

Introduction

Distributed generation is one of the policy priorities at the California Energy Commission. Very low emissions should give small gas turbine engines and microturbines a key role in providing distributed generation. They also have significant advantages in applications that combine heat and power. Unfortunately, the thermal efficiency of most small units is far less than that of central power plants and less than most reciprocating engines. Even with exhaust heat recuperation, microturbines convert only about 30 percent of the energy in fuel to electricity and about 70 percent to hot exhaust gasses. (By comparison, reciprocating engines convert 33 percent to 40 percent of the fuel to electricity when operating on natural gas.) While heat recovery equipment can exploit the energy in hot exhaust gasses, most applications require more electricity and less thermal energy; in addition, electricity has a higher economic value than thermal energy. Advances in thermal efficiency could increase the use of these engines in applications that require higher ratios of electricity to thermal energy.

More efficient electric conversion would allow greater use of microturbines in California. In many areas of California the requirement for (thermally driven) heating and cooling is low during much of the year. Producing more electricity without increasing the size of the engine would help satisfy customers' needs and reduce the demands on the electric grid. In this project the researcher proposed a turbine wheel that he predicted would boost overall engine efficiency by 30 percent when compared to engines of similar size operating at similar conditions. If he had achieved this improvement, micro-turbine efficiency would have risen to nearly 40 percent. An engine that combined heat recovery with 40 percent thermal efficiency would speed the deployment of distributed microturbines in California.

The researcher proposed to eliminate turbine-wheel losses by replacing the conventional radial turbine expander with an external-impulse turbine wheel (Figure 1). The researcher claimed two advantages to his design. First, it would convert kinetic energy losses associated with a radial or axial turbine expander into usable shaft energy. The researcher suggested that the impulse turbine would extract useful work from the kinetic energy of the nozzle, without significant exit losses and other moving blade losses. Second, the new turbine design could operate at a lower pressure ratio, facilitating high recuperator effectiveness. The researcher expected both advantages to lead to higher engine efficiency.



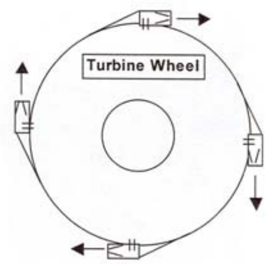


Figure 1: Proposed Recuperator External Impulse Turbine (REIT)

Objectives

This project was to determine the feasibility of a bladeless turbine wheel to increase the efficiency of small gas turbine engines. Nozzles on the periphery of the wheel provide the motive power. The researchers established the following project objectives:

1. Complete design of a nozzle assembly for a turbine wheel with one or more nozzle(s) and an approximate airflow of 275 lbs/hr.
2. Design wheel to achieve windage loss no greater than 2 percent and internal flow losses no greater than 1.5 percent (with compression factor compensation.)
3. Design and construct test rig for turbine wheel. Rig to sustain operation for 10 hours at full load at 1000^{o} F.
4. Test wheel to ensure mechanical integrity and demonstrate wheel and exit losses less than 7 percent.
5. Demonstrate overall system efficiency of 40 percent or greater at turbine inlet temperatures of 1700^{o} F for a wheel sized to a 50kW gas turbine engine.
6. Show, from project data, projected life-cycle cost of $0.05/kWh for a 50 kW gas turbine engine incorporating the bladeless turbine wheel.

Outcomes

1. The researcher completed final drawings of the wheel and test rig.
2. The researcher hired Inventive Turbomachinery Consultants, Inc., to estimate thermodynamic efficiency. The consultants found the researcher's estimate of turbine wheel efficiency to be incorrect by a factor of two. This large error was due to viewing the output of the wheel at rest (laboratory frame of reference) rather than spinning. The proposed wheel displayed no advantage over conventional wheels in a new estimate using the correct efficiency number.
3. The test rig was built.

4. After the researcher received the calculations from Inventive Turbomachinery Consultants, Inc., he decided not to fabricate a wheel. The project stopped at this point.
5. The wheel was neither built nor demonstrated.
6. The researcher collected no data allowing him to project energy costs.

Conclusions

The proposed wheel does not offer the advantages of increased thermodynamic efficiency as proposed by the researcher. This conclusion is based on the work of Inventive Turbomachinery Consultants, Inc. This wheel design will not produce additional energy over a conventional turbine wheel. Therefore, feasibility was not demonstrated.

1. The designs of the wheel and rig were completed prior to detailed analysis.
2. The researcher wisely sought outside counsel to validate the design calculations. The outside consultants found the fatal error in the original calculations. After correction of the error, the proposed wheel showed no advantage over conventional wheels.
3. Unfortunately, the researcher built the test rig in parallel with the analytical work to verify the performance of the wheel.
4. The turbine wheel was neither built nor tested. No conclusions can be drawn.
5. Since the wheel was not tested, its performance remains unknown.
6. Similarly, no data was gathered regarding the cost of energy produced by such a design.

Recommendations

Based on the calculations performed by the outside consultant, the program administrator recommends, as does the researcher of this project, that no further funds be spent advancing the bladeless turbine wheel concept evaluated in this project.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research would have been increased affordability of electricity in California. A more efficient turbine wheel for gas turbine engines under 5 MW would have increased efficiency from the low 20 percent range for unrecuperated micro-turbines and the low 30 percent range for small industrial turbines to over 40 percent. Small gas turbine engines with high efficiency and ultra-low emissions could have stimulated the installation of a greater number of distributed resources. The distributed gas turbines would have provided both excellent thermal efficiency and added reliability and security to the electrical distribution system. Unfortunately, this project was not successful. This makes any estimate of future benefits impossible.

Overall Technology Transition Assessment

As the basis for this assessment, the program administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The projects did not prove technical feasibility. Calculations by outside consultants showed that there is no efficiency advantage. Therefore, no connection to the market is required.

Engineering/Technical

Calculations by Inventive Turbomachinery Consultant, Inc., (San Diego California) showed efficiencies no better than conventional turbine wheels. An error was made in the original calculation performed by the principal investigator. The error reduced proposed efficiency by a factor of two.

Legal/Contractual

The researcher filed a preliminary patent application. He plans to withdraw the application now that the concept has been proven to be unfeasible.

Environmental, Safety, Risk Assessments/Quality Plans

Quality plans include reliability analysis, failure mode analysis, manufacturability, cost and maintainability analyses, hazard analysis, coordinated test plan, and product safety and environmental**.** No plans are required since there will be no subsequent work.

Production Readiness/Commercialization

No production readiness plans are required since the proposed turbine wheel did not prove to be feasible.

Appendix A: Final Report (under separate cover)

Attachment A – Grantee Report

INNOVATIVE WHEEL CONCEPT TO INCREASE GAS TURBINE EFFICIENCY

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Table of Contents

Abstract

The purpose of this project was to validate an innovative small gas turbine wheel concept which could be incorporated into a conventional recuperated Brayton-cycle gas turbine framework to achieve an efficiency of approximately 40% at a turbine inlet temperature of 1,700F. This new wheel concept is based on the elimination/reduction of "wheel exit" losses and the efficient operation at a low pressure ratio which together would produce a 30% increase in overall system efficiency when compared to other small radial or multi-staged axial flow machines (<5 megawatts) at similar operating temperatures. This efficiency gain is based on the use of the new wheel in a conventional recuperated Brayton cycle with all typical losses (nozzle losses, windage, pressure drops in recuperator and combustor, heat losses, etc.) accounted for in the cycle analysis. The advantages of this new wheel concept were twofold. Firstly, this new wheel idea would convert the exhaust loss (kinetic energy) indigenous to radial and axial flow machines which can be as high as 25 percent, and other losses associated with a rotating bladed wheel, e.g. clearance losses and cosine losses, into usable shaft energy. And secondly, the overall cycle using this new wheel could operate at very low rates of compression (2:1 for single stage and 4:1 for two stage) which allow for high rates of recuperation.

Preliminary and final drawings for the wheel and an experimental test stand were prepared as part of the scope of work. Also, a critical study was done to analyze more closely the losses and theoretical performance of the wheel prior to physical experimentation. The results of the study indicated that the net wheel output and performance would be substantially less than originally projected and these results led to a termination of the project. Furthermore, it is recommended that no future work be pursued regarding this type of wheel concept.

Key Words: turbine, wheel, microturbine, impulse, efficiency, Hero, radial, axial, sonic

Executive Summary

Introduction

Axial flow turbines, especially combustion turbines, provide motive power for both the generation of electricity and transportation. In addition, many turbines provide direct shaft horsepower for a variety of applications for pumping, manufacturing and compressing stations. The first combustion turbines were used primarily for military aircraft use since they have a high power to weight ratio; these military engines gave way to commercial aircraft in the early 1960's and finally combustion turbines were adapted for power generation in the succeeding decades. Today, small, so called micro turbines, provide electric power in the 25 to 100 kW range and the larger combustion turbines have outputs that exceed 200,000 kW's. The efficiency of these machines range from the mid twenty percent range to the low forty percent (lower heating value); typically, the smaller machines are less efficient than the larger machines. Due to today's volume manufacturing, the combustion turbines can be relatively inexpensive when compared to similar sized alternate methods of providing power or electricity. However, they exhibit a lower efficiency than typical internal combustion machines especially in the small sizes. This project proposed a new method to capture additional energy in the high velocity exhaust stream that exits the turbine and thereby potentially increase the electrical conversion efficiency to levels substantially exceeding the current state of the art.

Project Objectives

The objective of this project is to build and test the feasibility of a novel new small gas turbine wheel which, when incorporated into a conventional recuperated Brayton cycle, will achieve efficiencies approaching 40% at a turbine inlet temperature of 1,700F. This efficiency is estimated to be approximately 30% greater than other small radial or multi-staged axial flow machines. The demonstration of the wheel's effectiveness would show that most of the traditional "wheel" losses associated with small gas or microturbines using radial or axial flow turbine wheels would be eliminated or significantly reduced resulting in higher turbine wheel output.

Markron Technologies LLC ("Markron") proposed do a "proof of concept" to validate the concept of eliminating/reducing turbine wheel losses by using a recuperated external impulse turbine wheel, referred to as "the wheel". Although analysis from available sources and conversations with major turbine manufacturers (United Technologies, Siemens, and Solar Turbines) and on-going research, e.g. Ramgen, indicated no "fatal flaw" in the concept, actual flow patterns, fluid flow losses and other heretofore unidentified losses remain only an educated estimate and have not been quantified or verified.

Once the wheel was demonstrated, Markron proposed to extrapolate the wheel's performance in a recuperated Brayton cycle since the other losses associated with a Brayton cycle such as recuperator pressure drops (on both hot and cold side), combustor pressure drops, convective and radiant heat losses from turbine and associated equipment, compressor losses (as measured by isentropic efficiency), generator and inverter efficiencies and various auxiliary losses such as piping losses, bearing losses, fluid losses, instrumentation, and etc. have long been identified. For the tests involved as part of this project, Markron planned to measure those potential wheel and nozzle losses that would directly impact our new wheel concept.

Specifically, the following parameters were to be measured:

- Windage;

- Nozzle losses;
- Auxiliary and miscellaneous losses;
- Thermal losses;
- Fluid losses (from entry into wheel to nozzle exit); and
- Speed and torque of wheel based on static, free spin and dynamic load tests.

Based on the parameters listed above, the wheel's net turbine output would be measured; the total net output of a combustion turbine using our wheel could then be measured by estimating the amount of compressor power that would be required in a typical combustion turbine. The measured wheel net output minus the amount of expected power for compression would yield the results of this proof of concept.

Project Outcome

Preliminary and final drawings of the wheel and testing rig (Appendices II-VI) were prepared and the testing rig was assembled. However, prior to the actual construction of the wheel, the forecast of exactly how much energy the wheel would produce became suspect. To ensure that the concept of the wheel was still valid, the firm conducting the fabrication and testing (Alturdyne) hired an independent investigator to estimate thermodynamic efficiency. This report ("Innovative Turbine Wheel Design" prepared by Innovative Turbomachinery Consultants (see Appendix VII) showed that a thorough thermodynamic analysis indicated that the proposed wheel output estimate would have to be reduced by a factor of exactly "two" (2). This dramatic reduction in gross output was the result of viewing the output from a stationary viewpoint (laboratory frame) instead of a spinning wheel perspective. This change of reference point biased the estimate for a factor of "two" (2). Consequently, the amount of energy (theoretical maximum) that could be expected from the proposed wheel was halved. Once the compressor work was deducted from the overall gross output, the net output reduction would obviously be very significant and the concept loses its viability compared to conventional combustion turbine technologies. Accordingly, notwithstanding the prior reviews and consultation with other combustion turbine firms (including Westinghouse and United Technologies), the concept had a "fatal flaw" which rendered the wheel significantly less effective than originally projected thereby eliminating the prospects of commercial feasibility.

Conclusion

After a thorough delineation and understanding of the proposed wheel concept, it has been determined through expert analysis that this concept will not produce the additional amount energy when compared to conventional turbines. When viewed from the laboratory frame, the exit losses are the same as with a conventional turbine.

Recommendations

Based on the work of the outside consultant and further review with Alturdyne, no further work is recommended and no further research should be pursued. Prior to approval, the concept had appeared to be thoroughly vetted by both Markron, other combustion turbine firms, and the California Energy Commission's outside board of reviewers. While the review process entailed a thorough analysis by many skilled in the industry, the fatal flaw was only discovered after review by those who had specific skills in this particular area.

Introduction

Axial flow turbines, especially combustion turbines, provide motive power for both the generation of electricity and transportation. In addition, many turbines provide direct shaft horsepower for a variety of applications for pumping, manufacturing and compressing stations. The first combustion turbines were used primarily for military aircraft use since they have a high power to weight ratio; these military engines gave way to commercial aircraft in the early 1960's and finally combustion turbines were adapted for power generation in the succeeding decades.

Today, small, so called microturbines, provide electric power in the 25 to 300 kW range and the larger combustion turbines have outputs that exceed 200,000 kW's. The efficiency of these machines range from the mid twenty percent range to the low forty percent (lower heating value); typically, the smaller machines are less efficient than the larger machines. Performance of smaller machines are hampered by lack of sophistication and technology available to the larger machines. In addition, the larger machines have multiple turbine stages which, proportionately, tends to mitigate the turbine's exhaust loss, i.e. the exhaust loss is relatively fixed and the more energy extracted from the turbine, the less impact the exhaust loss on the overall performance.

New concepts to enhance Brayton cycle turbines are relatively rare as evolutionary changes are the norm as opposed to revolutionary changes. Literature and patent searches indicate very few innovative concepts have been commercialized to substantially increase Brayton cycle performance. Normally, methods for Brayton cycle enhancement focus on metallurgical considerations and blade cooling methods to increase firing temperature, higher component efficiencies, recuperators that operate at higher temperatures and diffuser technology to minimize "stall".

The purpose of this project is to validate an innovative small gas turbine wheel concept which could be incorporated into a conventional recuperated Brayton-cycle gas turbine framework to achieve an efficiency of approximately 40% at a turbine inlet temperature of 1,700F. This new wheel concept is based on the elimination/reduction of "wheel exit" losses and the efficient operation at a low pressure ratio which together would produce a 30% increase in overall system efficiency when compared to other small radial or multi-staged axial flow machines (<5 megawatts) at similar operating temperatures.

Energy efficiency continues to be both a national and statewide priority as evidenced by the Department of Energy's $750 million ATS program and the California Energy Commission's $100+ million annual funding for energy efficient programs. The successful demonstration of the recuperated external impulse turbine wheel's elimination/reduction of wheel losses would lead to greater efficiency in small gas turbines (<5 Mw). Accordingly, the specific energy problem targeted by this effort is to remedy the lack of high efficiency small gas turbines and microturbines; the new technology after successful demonstration would allow follow-on work to develop a small gas turbine that rivals the efficiency of the larger "aero" turbines. Highly efficient small gas turbines have enormous potential to replace the use of high polluting and high maintenance reciprocating engines and to establish a new market in them.

Project Objective

The objective of this project is to demonstrate the validity and effectiveness of an innovative small gas turbine wheel concept referred to as a recuperated external impulse turbine wheel which, if successful, could be incorporated into a conventional recuperated Brayton-cycle gas turbine framework to achieve an efficiency of approximately 40% at a turbine inlet temperature of 1,700F. The foundation of Markron Technologies' turbine wheel concept is based on the elimination/reduction of "wheel exit" losses and the efficient operation at low pressure ratio which together were projected to produce a 30% increase in overall system efficiency when compared to other small radial or multi-staged axial flow machines (<5 Mw) at similar operating temperatures. This projected efficiency gain is based on the use of the wheel in a conventional recuperated Brayton cycle with all typical losses (nozzle losses, windage, pressure drops in recuperator and combustor, heat losses, etc.) accounted for in the cycle analysis. In this new wheel concept, the nozzles are moved from the fixed diaphragm to the periphery of the wheel itself.

The advantages of this new wheel design are twofold. Firstly, the new wheel converts the exhaust loss (kinetic energy) indigenous to radial and axial flow machines which can be as high as 25 percent, and other losses associated with a rotating bladed wheel, e.g. clearance losses and cosine losses, into usable shaft energy. And secondly, the wheel cycle operates at very low rates of compression (2:1 for single stage and 4:1 for two stage) which allow for high rates of recuperation. It can be shown that by eliminating the exit losses in single/double stage turbines and by operating at lower compression, higher efficiencies result when compared to conventional high pressure turbines operating at the same turbine inlet temperature.

The specific work to be performed in this project is the design, construction and testing of an experimental wheel to empirically determine its associated performance and validate the concept. Markron utilized the resources of Alturdyne (a local turbine manufacturer) to help perform the required tasks listed in the Statement of Work listed in Appendix I. While realistic analyses of the wheel performance and losses have been made, these losses and fluid flow characteristics have not been verified. Since the recuperated Brayton cycle losses have been verified by main stream turbine manufacturers, successful demonstration of the wheel properties could, in follow-up tasks and work efforts, result in the design of high efficiency small gas turbine. However, developing a fully working prototype turbine generator utilizing the recuperated external impulse wheel is not within the current scope of work submitted.

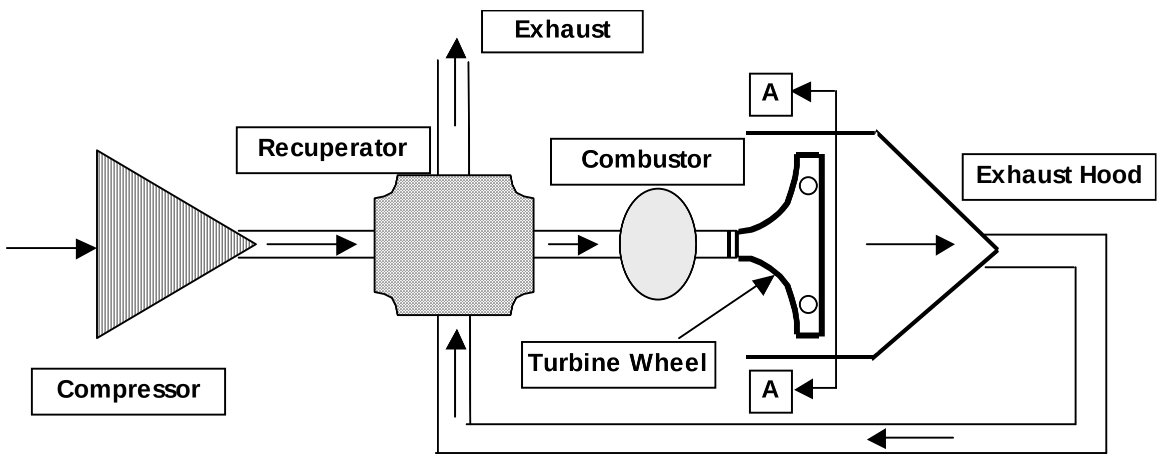
Project Approach

The project approach followed for this research effort was to first to characterize and define the concept and then identify how the new technology was expected to improve existing combustion turbine technology. Next, a procedure was developed to ascertain the "proof of concept" at minimum cost and risk. Following this step, the manner of determining the "proof of concept" was then broken down into specific tasks that could be planned, implemented, measured and verified.

Project Concept

The proposed concept directly uses the kinetic energy in the mass flow rate of the working fluid and does not require "staging" to yield high thermal efficiency. The concept described utilizes what is referred to as a "recuperated external impulse turbine" type of turbine wheel. Such single stage turbines, in the range of several hundred kW's to approximately several Mw's in size could be used in a wide variety of uses including motive power that is currently provided by reciprocating engines and combustion turbines. Multiple wheels could also be incorporated that would increase the practical size of the concept to approximately the 10-15 Mw range.

The wheel concept operates on a typical recuperated Brayton cycle and incorporates an external rotating turbine wheel that is powered by external rotating nozzles. The wheel is rotated by the reaction of these nozzle(s) acting on the outer peripheral of the wheel providing thrust and resulting torque that spins the wheel. The nozzles emit the working fluid at or close to sonic velocity to provide maximum thrust. By using the kinetic energy directly, the turbine stage is greatly simplified and made more efficient by the elimination of the impulse stage "moving blade's" exit loss. This wheel concept is not new, of course, having been described 2,000 years ago (Hero's wheel); however, the use of this wheel in the Brayton cycle is new and was estimated by Markron to produce significant efficiency advantages.



The recuperated external impulse turbine wheel was believed to be inherently more efficient than a conventional turbine section of a typical combustion turbine because of the elimination of losses. The ability of this turbine wheel to extract useful work from the kinetic energy of the nozzle, without significant exit losses and other moving blade losses, would allow for a significant increase in the overall cycle efficiency. In addition, due to the low work of compression required, high amounts of recuperation would be possible resulting from the low compressor exit temperature.

Referencing the figure above, the overall cycle is described as follows. Air is compressed to the "critical" pressure ratio (1.894:1), which is required to produce sonic velocity in a nozzle. Over pressurization results in the nozzle being "choked" and merely adds unnecessary compressor work to the cycle. After allowing for losses and compressor inefficiency, the recommended pressure ratio is approximately 2.1:1. The compression heated and pressurized gas is then preheated in the recuperator. The low pressure ratio is ideal for a recuperated cycle since increasing the working fluid temperature to the combustor significantly enhances thermodynamic efficiency.

It is most important to identify the fact that the net turbine output can be increased by higher turbine (nozzle) temperature but the pressure ratio always remains the same; accordingly, the compressor work always remains the same. This results in unusually high efficiencies and a cycle that more closely approximates Carnot since any differential increase in gross turbine output is added to the net output and no additional work of compression is required.

After the gas is preheated in the recuperator, further heat is added by the addition of fuel in the combustor. The pressurized and heated air is then directed to the rotating wheel where internal ducts direct the flow to the nozzles on the wheel's peripheral. The nozzles then convert the pressurized and heated gas into high velocity gasses approaching Mach number 1.0. The kinetic energy of exiting gasses provides the thrust that spins the wheel. After the exhaust gas exits at near atmospheric pressure, a collector or "Exhaust Hood" is used to gather the heated exhaust for recuperation of heat. After recuperation, the working fluid is exhausted to the ambient several hundred degrees below conventional recuperated machines.

Approach for Determining Quantification of Results

The actual wheel tests were not performed since the "fatal flaw" discovery would have rendered any measurements meaningless. Accordingly, the purpose of this section is to identify the approach on how the proposed tasks and performance objectives (see Appendix I, "Statement of Work"**)** would be accomplished. In order to measure the overall effectiveness of the wheel, specific test parameters were to be measured that then could be extrapolated into a complete Brayton cycle. After consultation with the selected turbine designer (Alturdyne), the following tasks were determined:

1. Develop specifications and design for nozzles and nozzle assembly apparatus and ensure overall apparatus fits with testing rig.

A design and specification was prepared for the nozzles and nozzle assembly (see Appendix II). The primary concern regarding this task was the symmetry of the nozzle design to help ensure that a smooth jet velocity from multiple nozzles would not have undue vibration and unequal force vectors in the wheel. This design had close tolerances to help ensure a balanced wheel design.

2. Develop specification and design for wheel assembly and seals.

The flow of gasses into the wheel was of paramount importance since improper flows would result in unequal flow distribution across the plane of the wheel entrance, i.e. the entrance into the spinning wheel. Care was used to prepare a design (see Appendices II, III, and IV) that allowed an orderly reduction of flow paths at a calculated angle such that minimal flow disruption was expected to occur. This "angle of reduction" was determined to be between 22 and 26 degrees. Also of importance was the necessity of robust sealing to minimize losses and thus the need for a special seal design (see Appendix V).

3. Fabrication of the Test Stand

A primary reason for the selection of Alturdyne for the design and fabricator of our wheel concept was its extensive prior work in the area of small turbomachinery and its possession of an already deployed small gas turbine and test stand. This small gas turbine and test set-up was located at the Alturdyne manufacturing facility near San Diego, California. Alturdyne does a significant amount of work for Solar Turbines (San Diego) and performs "packaging" and maintenance on many Solar products. The gas turbine mentioned above was acquired from Solar Turbines and had a sufficiently sized compressor section such that bleed air could be used at the proper flow and pressure to test the wheel. Only minor modifications were needed to set up the testing for the test wheel.

The actual layout of the "proof of concept" wheel is illustrated in Appendix VI. This pre-prototype wheel would have been tested using the bleed air and testing components of the Solar gas turbine described above. In addition, a burner was planned to be added such that the wheel could be tested close to the operating temperature expected in commercial operation. However, this was not planned to be an extended test as the overall purpose of the wheel design was merely to test the principle and not to design a commercial wheel or even a prototype that would have been suitable for production.

Specific testing of the wheel was not performed. Please see next section “Project Outcomes” for a discussion of the discovered “fatal flaw”.

Project Outcome

Although significant time and energy were expended to design the wheel and to modify an existing testing rig such that the test wheel could be demonstrated, an independent and outside consultant, Innovative Turbomachinery Consultants (ITC), had been retained to perform a detailed study on the concept wheel prior to fabrication. The results of ITC's analysis (see Appendix VII) showed that the wheel would only produce ½ of the expected output (see "Ideal Hp" equation on page 6 of Appendix VII). Such a drastic reduction in expected output would have rendered a commercial wheel impractical. This potential for a “fatal flaw” was first identified by Markron in its status report for the period of 3/17/04 – 6/17/04. In this report, Markron wrote:

> *The “frame of reference” is also a concern when evaluating the overall efficiency of the wheel. This is the reference point from which energy is produced. Siemens had raised this question initially last year when Markron visited their research facilities in Pittsburgh; however, ultimately Siemens concurred with the design of Markron. Under the frame of reference scenario, the overall wheel output will only be ½ of the kinetic energy produced. Markron has also showed its design to United Technologies and the DOE and this concern was not raised. It is somewhat of a philosophical argument but Markron feels there would be a violation of the conservation of energy is this is the case. Ultimately, testing will demonstrate that all kinetic energy must be accounted for.*

However, while this concern was raised, evaluation by the Department of Energy (DOE) did not raise the issue and, indeed, United Technologies had suggested that they were using a similar technology to reduce the exhaust losses from their conventional combustion turbines using reaction type blading.

The fundamental flaw regarding the frame of reference is the relative velocity of the escaping gasses leaving the blade. The blade or nozzle efficiency of a tip mounted nozzle having an efficiency of 100%, such as was assumed for the proposed wheel when philosophical “pure” reversible expansion of the gas, was assumed in this case. Thus a blade efficiency of 100% means that the work is exactly equal to the kinetic energy of the fluid entering the spinning nozzle and that the kinetic energy of the gas velocity leaving the nozzle from a laboratory reference point (i.e. a “fixed” observer as opposed to an observer moving with the spinning nozzle) is zero.

However, the fluid must have some kinetic energy or axial velocity to flow out of the blade/nozzle if it is going to move away from the spinning wheel. As this exiting velocity approaches zero (to the fixed observer) then the efficiency approaches 100%. But in this case, the gasses do not have sufficient energy to leave the spinning nozzle given that the nozzle is moving at the same velocity of the spinning gasses. This relationship to blade or spinning nozzle efficiency is a function of the speed ratio of the blade speed ratio of V_b to V_n where the subscript b refers to the velocity of the blade and the subscript n refers to the velocity of the spinning nozzle. In order to maximize the output of the spinning nozzle to the exiting gas velocity, the spinning nozzle velocity must be ½ of the blade speed. This blade speed ratio is also valid for straight impulse type turbines and, although initially thought not to apply when the nozzle is relocated to the periphery of the wheel, it does apply in this instance.

Due to this discovery, no wheel was manufactured as the results would have shown no difference than from a standard impulse type wheel and, therefore, there would have been no actual benefit from this type of wheel. Indeed, to produce the same results as a typical impulse wheel would have been challenging in itself as the recuperated external impulse turbine wheel also introduces new losses to the impulse concept. These losses were the primary reason why a pre-prototype demonstration of concept was to be conducted. However, given that this wheel was to be significantly more efficient than a traditional impulse wheel, strong rationale, at the time, indicated that these new losses would not result in significant losses given the significant amount of energy recovery forecasted for the proposed wheel.

Conclusions

The conclusions of these tests indicate that a well organized testing procedure identified a “fatal flaw” before more time, energy and money was spent to follow up the concept. Markron personally discussed this concept in detail with both Westinghouse and United Technologies with no strong negatives regarding the overall concept, although both companies wanted to see a proof of concept prior to participating further in the testing outcome.

Recommendations

Based on the work of the outside consultant and further review with Alturdyne, no further work is recommended and no further research should be pursued. Prior to approval, the concept had appeared to be thoroughly vetted by both Markron, other combustion turbine firms, and the California Energy Commission's outside board of reviewers. While the review process entailed a thorough analysis by many skilled in the industry, the fatal flaw was only discovered after review by those who had specific skills in this particular area.

Appendix I-VII

Please contact the awardee for a copy of these appendices.